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A PROGRAMMABLE DYNAMIC THERMAL VACUUM SYSTEM FOR
SOLAR ARRAY COMPONENT TESTING

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ABSTRACT: The Programmable Dynamic Thermal Vacuum System (PDTVS) was designed to provide long-term laboratory evaluation of solar array components undergoing thermal cyclic effects anticipated for specific missions. This system is capable of duplicating the temperature excursions, including rate-of-change of temperature, for practically all missions currently under consideration at NASA. The equipment can obtain test specimen temperatures between +150°C to -120°C with a rate-of-change of at least 6°C/min. The PDTVS can accommodate thirty-six 6"x6" test specimen holders and position each one in front of a illumination port for periodic in-situ electrical measurements with a solar simulator.

Basically, the facility consists of an ion-pump vacuum system with 2 bell jars, thermal conditioning equipment, a 3 stage blower, a programmable control unit and an LN₂ storage tank. The novel developments in this system include a high-energy low-mass heater which employs radiative-convective coupling of a gas stream to an IR source. The test carrousel shaft is used for specimen positioning and as an instrumentation penetration. Initial difficulties required modification of the blower bearings, shaft and housing to accommodate the wide range of gas stream temperatures without affecting performance.

KEY WORDS: Solar cell, solar array, thermal cycle vacuum testing, gaseous nitrogen heater, gas stream blower, thermal shroud, GN temperature conditioning.

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INTRODUCTION

The ability of solar arrays to provide the power requirements for missions now in the conceptual and preliminary design stages at NASA require thermal cycling data which is not now available. Problems have been encountered on previous projects with the solar cell-interconnector solder joint and/or the solar cell contact integrity that have been solved primarily by "cut and try" techniques. Part of the problem stems from the broad range of thermal conductivities of the conductive and non-conductive components which comprise the solar array. The array assembly with this inherent thermal mismatch must undergo repeated thermal excursions typically with a ΔT as high as 230°C . Current design thermal flight qualification procedure generally consists of subjecting the prototype solar panel or paddle to a few thermal vacuum cycles to extremes about 10% beyond maximum and minimum flight predicted temperatures. Usually there are no more than rudimentary steps taken to ensure that the rate-of-change of temperature during shadow encounter and emergence is reproduced.

Consideration of some of the specific missions being planned, should assist in defining the test equipment requirements. The Orbiting Astronomical Observatory (OAO) program is seriously considering a ten-year life requirement for the solar array, which means approximately 50,000 thermal cycles (Ref. 1). Data on conventional solder connected cells indicates problems can be anticipated after 3,000 cycles (Ref. 2). The Astronomy Explorer (AE) C&D will encounter significant aerodynamic heating during a series of low perigee passes (Ref. 3). Considerable interest is also expressed in solar array capabilities on close-approach solar missions as well as the capability to operate in the vicinity of Jupiter. Perhaps of equal importance is the need to obtain comparative long-term thermal vacuum test data on solar array components or composites generated in Research and Development (R&D) programs which have the potential of cost saving, improved performance, weight reduction and/or increased reliability. The current conservative philosophy of flying with proven components has generated a significant time lag between R&D and flight utilization despite potential technical and/or economic advantages.

The Programmable Dynamic Thermal Vacuum System (PDTVS) was designed to support flight projects in the preliminary solar array design stage and as problems are encountered during flight qualification. In addition, the PDTVS provides meaningful long-term thermal cyclic effects data on R&D program developments which enhances their implementation in flight programs. In order to achieve these design objectives, the following system requirements were developed.

DESIGN REQUIREMENTS

The requirements generated for the PDTVS were as follows:

1. The system must be able to reproduce thermal conditions anticipated for essentially all NASA missions under consideration for the 70's which would employ solar arrays.
 - a. Specifically operate between +150°C to -170°C and produce a rate-of-change of at least 6°C/min. between +150°C and -120°C.
2. Provision must be incorporated to accommodate in-situ periodic electrical measurements of test specimens through an illumination port.
 - a. Each of thirty six 6"x6" test specimens must be mounted so that it can be accurately positioned in front of the illumination port.
 - b. Also must be capable of accommodating an IMP-I solar panel.
3. Each test specimen must have a 99% view factor to thermally controlled surfaces.
4. Test instrumentation wiring shall produce minimum interference to the thermal view factor.
5. System must be capable of programmable thermal cycling performance.
6. System must operate automatically over long periods (on the order of 3 to 9 months).
 - a. Fail-safe features must be included.
 - b. Permit ready accessibility for operational and maintenance functions.
7. Must incorporate features that provide economical operation, including low-level maintenance requirements.
8. A second chamber shall be incorporated such that it could be thermally slaved to the programmed thermal cycle. This chamber would accommodate small numbers of samples which could be removed without affecting the long-term testing on the larger unit.
9. A common roughing system shall service both chambers with capability for a third chamber.

The above requirements have been incorporated in the PDTVS, which was built on-contract for the Goddard Space Flight Center.

OVERALL FACILITY

The PDTVS facility is shown in Figure 1.

The major components which comprise the PDTVS facility are a getter-ion pump vacuum system with two bell jars, a solar simulator, a test carousel with automatic indexing, thermal conditioning system, programmable controls, liquid nitrogen storage tank and associated piping. Several innovative features were incorporated in the thermal conditioning equipment and in the test carousel positioning scheme.

VACUUM SYSTEM

Roughing for both bell jars is achieved through physical adsorption of gas molecules by LN₂ cooled high-capacity molecular sieves. Pumping into the high vacuum region is accomplished by sputter-ion pump combined with titanium sublimation pumping. The sputter-ion pump operation involves trapping gas molecules and atoms through the interaction of gas ionization, titanium sputtering, chemical combination and ion burial. The titanium sublimation pump sublimates titanium from heated filaments which is deposited on a "line-of-sight" transmission to shielded non-working area. Pumping is affected as the active gases combine chemically with this deposited titanium film to form stable compounds. This system provides pressures of 10⁻⁶ torr and below under typical test conditions.

The getter-ion pumping system was chosen rather than systems that involve introduction of long-chain hydro-carbons. The combination sublimation and sputtering-ion pump system was considered developed sufficiently to meet the long-term automated operational requirements. This system is essentially immune from failures in power, water or air-service.

The 24" diameter bell jar was chosen as it could accommodate an Interplanetary Monitoring Platform (IMP)-I solar array panel within the thermal shroud. The IMP-I panel will probably be the standard design for the next series of in-house spacecraft at the Goddard Space Flight Center. This particular size bell jar was available as a standard size in the industry. The 12" bell jar was designed to accommodate a smaller number of test specimens. This feature would permit periodic removal of specimens for optical inspection and testing without interrupting the long-term thermal cycling test. Both bell jars are fitted with an illumination port of UV-grade fused quartz to permit in-situ solar

illumination measurements. Calibrated standard cells and disc radiometers are mounted to insure the desired solar illumination intensity level. The spectral distribution of the simulator can be checked with a spectrophotometer in the same lab.

THERMAL CONDITIONING SYSTEM

The Thermal Conditioning System (TCS) was designed to provide temperature stabilized GN or LN₂ to the cryoshroud of either of the two or both of the bell jars. The TCS supplies gaseous nitrogen to the selected bell jar shroud at any temperature between -170°C and +150°C with a maximum shroud temperature difference of ±4°C while the shroud is under a distributed thermal load of 140 watts. High flow rates of thermally conditioned gaseous nitrogen transform the shroud into the necessary radiation heat source and/or heat sink to obtain the desired test specimen temperature.

Test specimen heating and cooling is effected by radiation coupling between the shroud and the sample. The thermal shroud system includes a movable shutter in the illumination port and an optically dense baffle which shields the vacuum system internals. The only constraint preventing a 100% view or thermal shape factor from any point on a test panel to a controlled thermal surface is the carousel shaft.

The shroud wall rate of temperature change is sufficiently rapid to produce a 6°C/min. change in specimen temperature at any level between +150°C and -120°C. The specimen specific weight and surface emissivity have a large effect on the attainable rate-of-change of temperature. The value of 6°C/min. is obtainable with silicon solar cells having fused silica coverslides attached such that the composite has a specific weight of 0.83 lbs/ft² or less.

Modulating butterfly valves proportion the gas flow through the GN to LN₂ heat exchanger. This flow variation combined with a controlled power input to the heaters produces a very precise means of affecting temperature control. There is also a large potential heat source or heat sink reserve. The response time and temperature overshoot of the system are minimized by biasing the system source and sink against each other.

The basic components in the TCS are (1) a high-energy density low-mass heater; (2) a three-stage centrifugal blower, and; (3) a liquid nitrogen boiler. These components, their inter-connecting piping and associated controls (LN₂ level, blower power, high and low temperature interlocks, etc.) are mounted in a caster mounted 2.5'x4.5'x6'

equipment cabinet. A block diagram of the system is shown in Figure 2. The TCS components are briefly described as follows:

- a. Blower: A three-stage centrifugal blower is used to circulate approximately 220 CFM of nitrogen gas through the system. This blower required considerable modification of a commercially available unit in order to operate with the range of gas temperatures involved. These modifications entailed the installation of super precision bearings, a polished stainless-steel shaft fitted with a specially designed fan and casing redesign to improve the heat dissipation. These modifications limited the bearing temperature excursions to a fraction of the GN temperature range.
- b. Heaters: Rapid transients require that system mass be minimized. This is particularly critical in the heater design as this element runs at the highest temperature of any system component. The system heater shells are fabricated from 3 inch diameter thin-wall stainless-steel tubing. Each heater module contains a 1.6 KW quartz IR lamp and a set of thin anodized aluminum fins. The fins are radiatively heated by the IR lamp and are convectively cooled by the GN stream. The weight of the heater extended surface is approximately one (1) lb.
- c. Boiler: The system heat sink is a LN₂ boiler. Gaseous nitrogen is pumped through the tube side of a shell and the tube heat exchanger. The shell side of this unit is flooded with LN₂. The liquid level is maintained with a temperature probe, controller, and solenoid valve. Boil-off LN₂ is mixed with the exit gas flow stream to aid in lowering the circulating gas stream temperature. A pressure relief valve is located in the main gas stream to prevent excessive pressure buildup either from the introduction of boil-off gas or from gas expansion during increasing temperature transients in the loop. The relief valve maintains the GN loop pressure at 3 psig.
- d. Control: Operational control is provided by a solid controller having proportional band, rate and reset functions and a dynamic setpoint programmer. The controller has a set point accuracy of $\pm 2^{\circ}\text{C}$.

Control is obtained by sensing the shroud wall temperature and comparing the measured value to either a fixed or dynamically programmed set point. The resulting error signal is amplified and transformed into a control voltage. This voltage is used to control the output

of a silicon control rectifier (SCR) and a pneumatic valve positioner. The valve positioner operates two butterfly valves which are 90° out of phase. The amount of cooling provided is determined by the ratio of the flow through the boiler to the flow through the boiler by-pass. The amount of heating provided is a function of the magnitude of the error signal and the output of the SCR. There is sufficient overlap between the heating and cooling functions such that transitional operation is essentially continuous. This variation in flow combined with a variation in power input to the heaters produces a precise means of effecting temperature control. There is also a large potential heat source or heat sink reserve. The response time and temperature overshoot of the system can be minimized by biasing the system source and sink against each other. An over-temperature safety interlock using a pyrometer and relay automatically cuts out the heater voltage when the temperature hits a 150°C upper limit and automatically cuts the heater back in at 145°C if required by the programmed input. A schematic of the system control logic is presented in Figure 3.

TEST CARROUSEL

A carrousel, or test specimen holder, was designed to accommodate the maximum number of test specimens such that each specimen can be accurately positioned at the illumination port. The system thermal performance objectives required the carrousel to be extremely lightweight with minimal thermal mass. The carrousel design that emerged was duo-decagon frame that could accommodate thirty six 6"x6" test specimens. The specimens are mounted along the periphery of the carrousel in three adjacent rings. Thus, as the carrousel is rotated and/or translated, each of the test specimen holders is positioned in front of the illumination port. Solar simulation is provided by a filtered 2500 watt Xenon arc lamp simulator which closely approximates the solar spectrum in space. This capability permits in-situ solar cell electrical characteristic measurements periodically during the test. A test section is included on the carrousel to calibrate the solar simulator illumination at the test plane. The solar simulator can be rotated such that its beam is directed at a spectrophotometer to periodically analyze the simulator's spectral distribution.

CARROUSEL POSITIONING

The initial design efforts to provide positioning of the carrousel at the illumination port involved various mechanical linkages with rotary and translatory motion feed throughs. These systems could be characterized as being complex, involving considerable thermal mass, imposing internal volumetric constraints, introducing conductive thermal paths and requiring more than one shroud penetration. A novel

approach to the positioning problem was suggested by Maurice Cridlin of the Goddard Space Flight Center. He had devised a sample positioning scheme for a facility that required in-situ measurements of particle radiation effects on the solar absorptance of materials (Ref. 4). This scheme involved attaching the carrousel to a hollow vertical shaft on the center-line. On the PDTVS the shaft penetrates the thermal shroud and bell jar and provides a means of indexing the carrousel through physical movement of the shaft. Additionally, the hollow shaft provides an instrumentation penetration.

The vacuum seal around this shaft is maintained by use of an ante-chamber with two viton "O" rings adjacent to the bell jar. This method requires a roughing pump to separately maintain approximately 10^{-3} torr vacuum in the ante-chamber.

Test specimen positioning accuracy was increased and test time was reduced by the addition of two remote controlled motors. One motor provides the desired vertical movement to align any one of the three rings of specimen holders at the plane of the illumination port by moving the shaft and the rotational indexing platform. The second motor, which is mounted on the rotary indexing platform, indexes each of the twelve specimen holders comprising the ring. This rotary motion is restricted by stops to $\pm 180^\circ$ in order to minimize instrumentation lead movement. The alternate approach of using instrumentation slip rings was considered to introduce unwarranted problems.

Instrumentation capability is increased by the use of a stepping switch installed in the carrousel. This switch connects the instrumentation leads to each of the three rings on command. Thus, only forty leads are fed through the shaft. The leads are potted in the shaft to sustain vacuum.

PERFORMANCE TESTING

The TCS was performance tested and found to meet the program design goals. The actual transient performance of the system is shown in Figures 4 and 5.

The initial cooldown rate from a steady state temperature of 20°C was 14°C per min. for the shroud wall and 6°C per min. for the test specimen.

The initial cooldown rate from a steady state temperature of 150°C was $25^\circ\text{C}/\text{min.}$ for the shroud wall and 11°C per min. for the test specimen.

The initial heat up rate from -140°C was reduced somewhat by the fact that the shroud wall and test specimen were not in thermal equilibrium at the time the test was initiated. The initial heat up rates from -140°C were approximately $10^{\circ}\text{C}/\text{min.}$ for the shroud wall and $7^{\circ}\text{C}/\text{min.}$ for the test specimen.

The initial heat up rate from a steady state temperature of 20°C was $4.1^{\circ}\text{C}/\text{min.}$ for the shroud wall and $3.4^{\circ}\text{C}/\text{min.}$ for the test specimen.

The rapid temperature change of the shroud wall and the close coupling between the wall and the specimen are particularly relevant.

Operation in the flooded LN_2 mode was conducted during Acceptance Testing. The results of the flooded LN_2 mode test are shown in Figure 6.

CONCLUSIONS

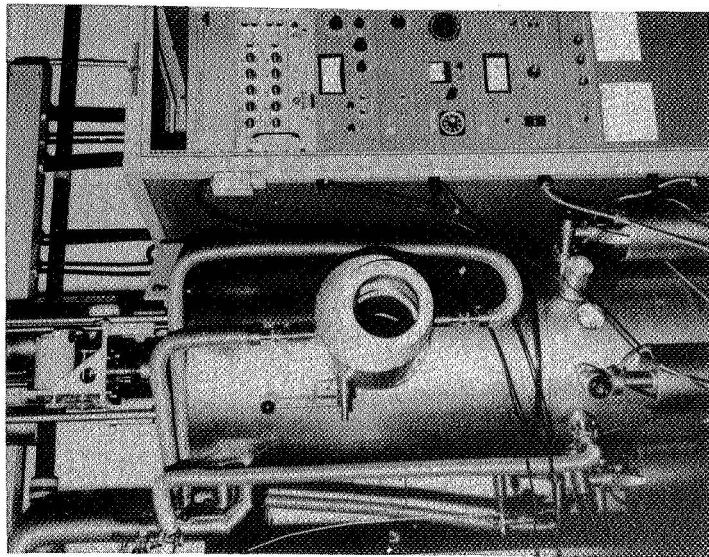
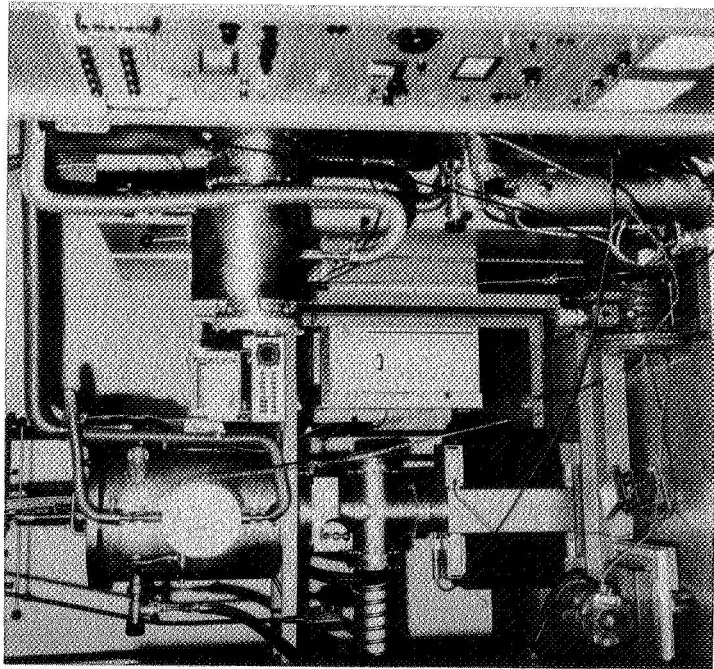
The PDTVS provides a test capability previously unavailable for solar array components. This capability is necessary to evaluate candidate components for the more exacting requirements of currently contemplated space missions. Specifically, it provides the following capabilities for solar array component testing:

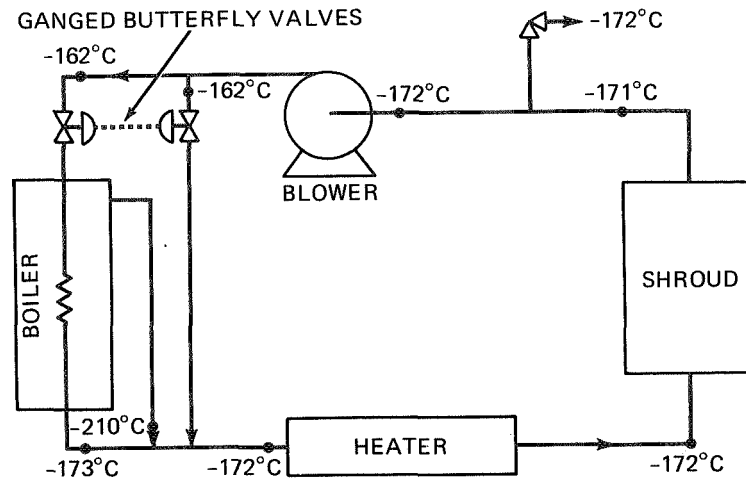
1. PDTVS can accurately reproduce the rate-of-change of temperatures experienced by solar arrays in typical orbits and in a wide range of probe missions.
2. It is programmable to reproduce desired thermal orbital conditions on a long-term basis and with a statistically significant number of solar array components.
3. It enables in-situ solar cell measurements to be taken periodically during long-term thermal vacuum testing.
4. PDTVS is automated for unattended operation. Safety devices will shut down equipment in the event of malfunction.

The PDTVS incorporates several novel design innovations. The high energy density-low mass heater developed for this system was a novel application of radiative-convective coupling of a gas stream to an IR source. The carousel shaft use for positioning and as an instrumentation penetration was an adaption of a recent GSFC development. Modification of the blower to allow operation over the potentially troublesome range of GN temperatures presented a formidable design challenge.

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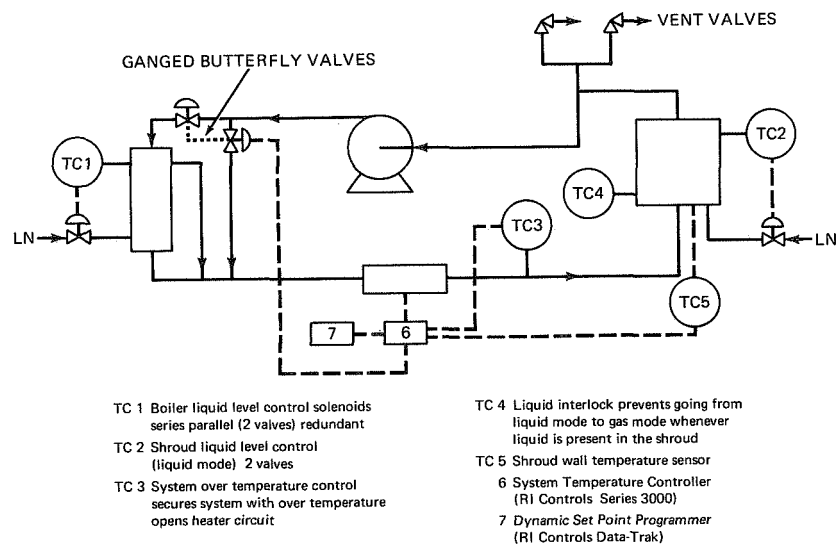
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NOTE:
GN temperature shown for steady state operation at -170°C .

Fig. 2—System block diagram



TC 1 Boiler liquid level control solenoids
series parallel (2 valves) redundant
TC 2 Shroud liquid level control
(liquid mode) 2 valves
TC 3 System over temperature control
secures system with over temperature
opens heater circuit

TC 4 Liquid interlock prevents going from
liquid mode to gas mode whenever
liquid is present in the shroud
TC 5 Shroud wall temperature sensor
6 System Temperature Controller
(RI Controls Series 3000)
7 Dynamic Set Point Programmer
(RI Controls Data-Trak)

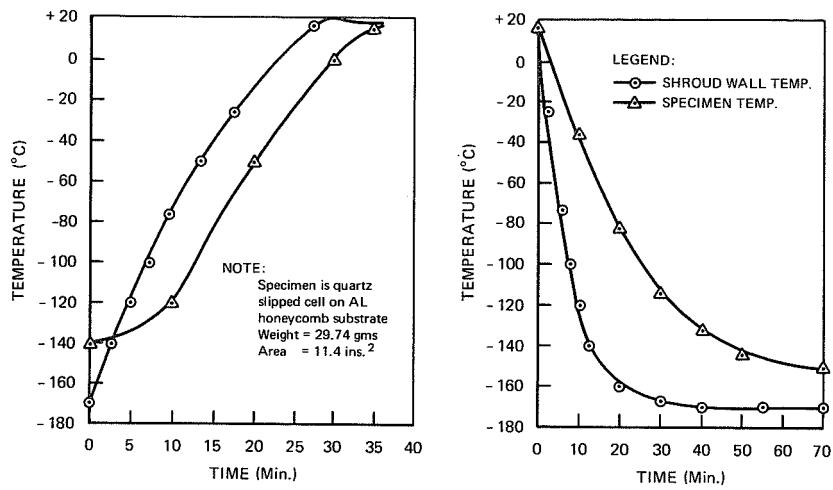


Fig. 4—System transient performance

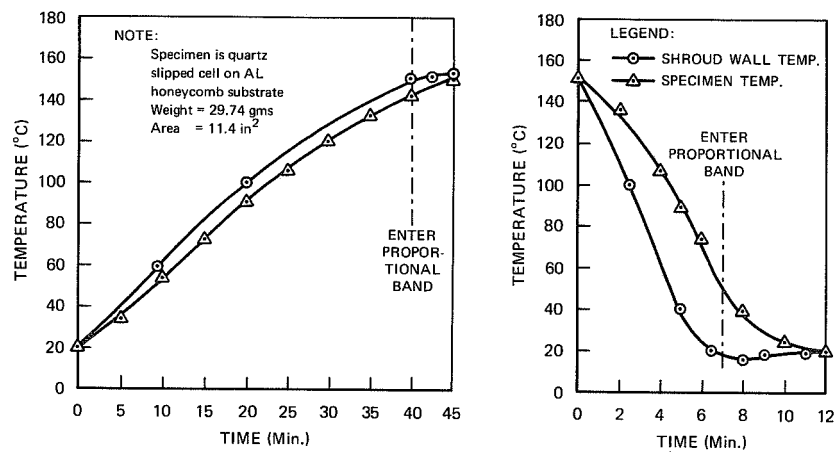


Fig. 5—System transient response

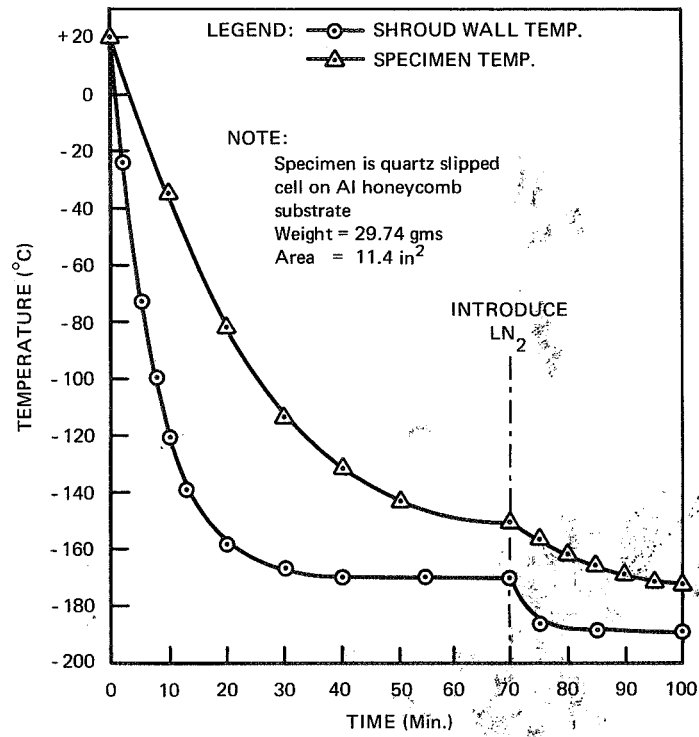


Fig. 6—Liquid nitrogen mode operation